

**A Report for**  
**CDM Federal Programs Corporation**  
**3201 Jermantown Road**  
**Fairfax, VA 22030**  
**Contract from USACE: W912DQ-11-D-3004**

***Burial and Burrowing Depth of Infaunal Organisms from the Passaic River,  
New Jersey***

**May 2014**

**Robert S. Prezant, Ph.D., Consultant**  
**15 Fairview Avenue, West Orange NJ 07052**  
**prezantr@mail.montclair.edu**

## ***Burial and Burrowing Depth of Infaunal Organisms from the Passaic River, New Jersey***

Animal-sediment relationships in aquatic environments have been heavily studied (Reinharz and O'Connell, 1983; Whitlatch, 1981; Snelgrove and Butman, 1994; Vaughn and Hakenkamp, 2001). Innumerable studies have focused on the pivotal interplay between organism and substratum in the realm of form and function. Burial and burrow depths can have a significant impact on the surrounding ecosystem, from interspecific interplay to altering water-sediment interface chemistry and structure. The intimate association between organism and substratum controls the viability of a given species in a given habitat. In turn the organism established within or on that substratum can alter the near and sometimes surrounding habitat and environment. Such is certainly the case in the benthos of the Passaic River. This report documents information found in the literature from other geographic regions on the vertical distribution of select benthic infaunal species found in the sediments of the Passaic River (Table 1). Some of the issues of animal-sediment relationship are briefly reviewed here as well as they relate to burrowing dynamics.

Burrowing activities by benthic invertebrates can have important ecological and environmental consequences, both simple and easily determined as well as complex and sometimes unexpected (Vaughn and Hakenkamp, 2001). The relative concentration or density of individual populations varies with taxon as well as sediment type, including texture, porosity, granulometric profile, and various geochemical properties. The infaunal organisms are often most abundant in the top 10cm of the sediment but penetrations to and beyond 30cm are common and essential in overall community and environmental dynamics (Reinharz and O'Connell, 1983).

Dense populations of burrowing biota can permeate the upper surfaces of benthic sediments creating a network that induces changes in near bottom water flow and subsequently changes in sediment type and texture. Werner and Rothhaupt (2007) note that bivalves, such as the Asian clam *Corbicula fluminea* (found in Passaic River), can act as "ecosystem engineers". Sediment perforations and organismal reworking of burrows or just the burrowing process itself can lead to changes in microbial communities and the associated biogeochemical environment (Kristensen and Kostka, 2005). Burrowing activities of *C. fluminea* changes oxygen uptake and nutrient flux along the surface of the benthic substratum as the clams burrowing induces release of reactive phosphorus, ammonium and nitrate from sediments (Zhang et al., 2011). Tubificid oligochaetes, including *Limnodrilus claparedeianus* (a species found in the Passaic River) can alter redox potential and pH (Davis, 1974). Waldbusser et al. (2004) found differences in biogeochemical parameters such as pH and oxygen, as well as flux rate differences in oxygen and phosphate, reflecting changes in infaunal (burrowing taxa) species composition and assemblages. Similarly, Quintana et al. (2011) demonstrated that "porewater irrigation" from the polychaete *Marenzelleria viridis* (also found in Passaic River) brought oxygen-rich water and nutrients into the burrows

and could "have important associated ecological implications in the ecosystem". The capitellid polychaete (and inhabitant of the Passaic River) *Heteromastus filiformis* can burrow, head down, to in-sediment depths of 30 cm (Cadée, 1979). *H. filiformis* deposit feeds at the lower end of the tube that it constructs and this system and this worm has been used as a model for examining microhabitat changes in water and sediment chemistry (Abele et al., 1998). Distribution and diversity of benthic communities are also impacted by the relative abundance and type of infaunal burrowers (Schaffner, 1990). The latter reflects the bioturbation and sediment modification of benthic burrowing organisms that influence habitat available and appropriate for other organisms. For example, *Marenzelleria viridis*, a polychaete that lives in vertical burrows that can reach 30cm depth in muddy sediments (and is found in the Passaic River) seems to have an inverse population correlation with the polychaete *Nereis diversicolor* in a Netherlands estuary (Essink and Kleef, 1988). In this water body, when there are high population densities of *M. viridis* the population numbers for *N. diversicolor* decrease. There are populations of *Marenzelleria viridis* as well as the nereid *Alitta (Nereis) succinea* in the Passaic River although this relationship has not been studied.

Burrowing itself can simply be an additional means of avoiding consumption by surface and nektonic predators as is the case shown in the Choptank River where the infaunal bivalves *Mya arenaria* and *Macoma balthica* (both also inhabitants of the Passaic River), living deeper in the sediments, more readily avoided the blue crab, *Callinectes sapidus* (another Passaic River inhabitant) (Blundon and Kennedy, 1982; Edelaar, 2010). In fact, specimens of *Mya arenaria* will burrow more deeply in the presence of the green crab, *Carcinus maenas* (Flynn and Smee, 2010; Thomson and Gannon, 2013). Overlying algal mats can also influence burrowing depth. Burrowing depth is negatively correlated with sediment coverage by the green alga *Enteromorpha* sp. and *Cladophora* sp. in *Mya arenaria* (Auffrey et al., 2004). The presence of dense algal mats is in turn often a result of eutrophication. Thus in eutrophic situations that induce algal growth, at least soft-shell clams burrow less deeply and might in turn be more vulnerable to predation. On the other hand, infaunal burrowers can significantly modify sediment granulometric profiles. *Limnodrilus claparedeianus*, an oligochaete that has a wide distribution including the Passaic River, can modify sediment profiles down to at least 13cm (Ciutat et al., 2006). This reformulation of the sedimentary profile in turn can alter transport of fine particulates as well as dissolved substances along the sediment surface (Fukuhara et al., 1987).

### **Factors Influencing Feeding Modes and Foodweb, Sediment and Water Mixing**

Ecologists continue to struggle with fully understanding the relationship between food webs, biodiversity and energy flows within the ecosystem (Hussey et al. 2013; Jonsson, 2014; Sanders et al. 2014; Takahashi et al. 2013). As will be discussed below, even the ability to narrowly define feeding groups within the food web is not always clear (see Williams and Martinez (2004) where only 54% of the species in a diverse community were able to be "unambiguously assigned

to a discrete trophic level"). Equally important Dunne et al. (2004) suggest that environmental perturbations can permeate through a marine ecosystem and have an important influence in changing food web dynamics. These issues are important as there is an equally growing recognition that trophic cascades, reflected in complex food chains within a food web, are ultimately dependent not just on level one autotrophs but on the conditions and biota that are precursors to the latter primary producer's success (see Agrawal and Gopal, 2013; Reed and Martiny, 2013). Of particular note is the key function of bioturbation and organic input on sediment microbial community which in turn has an important role in sustaining infaunal deposit feeders and recycling nutrients into the system (see Krumins et al. 2013). Below is a brief review of how modifications in feeding modes of infaunal invertebrates, bioturbation, and sediment bacteria influence biodiversity and food webs.

Proportional analyses of feeding types that are used to define communities must be considered in light of the complex nature of the organisms and how those organisms might be influenced by environmental and temporal changes. The very nature of the biogenic, geological (sedimentary) and hydrologic cycles can diversify feeding modes and guilds as well as deeply connect ultimate food resources. Draft reports by the CPG represent (based on earlier benthic reports from Windward) that deposit feeders in the Passaic River obtain 70% of their nutrition from particulates, 15% from phytoplankton/algae and 15% from zooplankton. Similarly they note similar proportions and origins for benthic detritivores. Large benthic omnivores are listed as having a proportion of foods: 15% phytoplankton/algae, 15% zooplankton, 70% benthic detritivore. As well understood, predators have a larger range of food resources extending the food web to include phytoplankton and algae, detritivores, benthic omnivores, and a variety of macrofauna, both benthic and pelagic. The CPG consideration that the primary nutrient resources for pelagic fish resides in the top two centimeters of sediments minimizes the importance and relevance of bioturbation, growing recognition of the critical importance of meiofauna and infaunal bacteria, and feeding type plasticity. This section of the report briefly considers the importance of these parameters using a small fraction of literature available. Once again there is little relevant literature available that documents the comparative roles of bacteria, meiofauna, burrowing activities, etc. from the Passaic River.

Complexities in determining proportional allocation of food resources is a well known issue in ecological literature. The difficulties are sometimes reflected in similar proportional allocations of feeding types. Classic and important early work by Rhoads and Young (1970) offered conceptual frameworks for helping to define communities based on spatial separations induced by deposit versus suspension feeders. This early work was essential in helping us garner an early understanding of the benthos but as we have better understood individual organisms life cycles and life styles there is recognition that teasing feeding types apart is not clear cut. A closer look at the concept using "biological traits" (here reflecting specific feeding types) has revealed greater plasticity than previously thought. Rönner et al. (1988) and Esselink and Zwarts (1989)

determined that the polychaete *Hediste diversicolor* will suspension feed, deposit feed or convert to predation based on food or prey availability. Genera and species that are found in the Passaic River, such as *Alitta (Nereis)* and *Macoma*, have also been found to switch feeding mode from deposit to suspension feeding depending on time of year and food availability (Riisgård and Kamermans, 2001). Similarly, feeding switched from deposit feeding to suspension feeding in the tube-dwelling polychaete *Spiochaetopterus oculatus* under varying flow regime (Turner and Miller, 1991). Recently, and from a broader ecological perspective, Cesar and Frid (2012) found that while disturbance within an estuarine or intertidal habitat results in no change in overall biodiversity it can in fact yield an alteration in organismal behavior and thus biological traits including feeding mode. Recognizing the behavioral availability of changing mode of feeding should prompt a reanalysis of stages of community maturation. While "mature benthic communities" are considered to be dominated by detritivores and shallow deposit feeders there is a possibility that feeding styles can "switch".

Similar changes in feeding mode can take place seasonally. In at least one study (Swarts and Wasnink, 1989) the bivalve *Macoma balthica* burrowed twice as deeply in the winter (to 4-6 cm) than in the summer (1-4cm) both filter and deposit feeding in the summer but only filter feeding in the winter. Seasonal changes in burrowing behavior and depth also is related to relative survival. *M. balthica* burrows deeper in early winter, better avoiding predators, but moves up in the sediments in late winter to take advantage of higher food availability (moving from 8 to 2-4 cm sediment depths)(de Goeij and Luttikhuisen, 1998). Changes in burrowing depth can influence feeding behavior, growth rate and thus overall biotic role of an organism or population within a community and environment.

The role of benthic "engineers" in biologically, chemically and physically modifying sediments and thus habitats is well known and already briefly discussed. A review of how burrowing can modify substrata and in turn microbial and biogeochemical activities can be found in Kristensen and Kostka (2005). The relative importance of how modifications to the physical structures of the biotic community created by ecosystem engineering is reviewed by Sanders et al. (2014) who argue that these physical alterations can modify "food chain dynamics". The perforations in surface sediments created by burrowing benthic organisms are only a superficial appearance of the complex subterranean structures and activities that occur within, adjacent to and below the underlying burrows. Occupied burrows are frequently active construction and deconstruction zones with the occupants working and reworking the site. This activity creates not just localized changes in substratum but, through irrigation, a controlling feature in microbial community and population dynamics. Benthic infaunal engineers also modify the abiotic environment creating localized changes in pH, redox, and sediment composition and quality (see Jones et al., 2010) and can do this down to maximum burrowing depths. Distribution and normal microbial processes within these sediments in turn are important features in the movement of solutes between the burrow environment, the overlying water column, and the surrounding sediment

including biogeochemical fluxes, and changes in nitrogen and phosphorus cycling (Braeckman et al., 2010; Davenport et al., 2012; Holmer et al., 1997; Laverock et al., 2011; Kristensen and Kostka, 2005; Moodley et al., 1998; Nascimento et al., 2014; ). Not specifically relevant to the Passaic River but of relevant interest, Rhoads and Boyer (1982) note that benthic infaunal organisms worldwide have burrows that range from just a couple of centimeters to tens of centimeters with an average bioturbation depth of 9.8cm. While individual burrows and burrow walls vary with species (see Aller, 1983 and review in Kristensen and Kostka, 2005), these approximations are offered to better appreciate the distance-impact infaunal burrows can have on surrounding sediment chemistry. Burrows and burrowing channels are not silos.

Of importance are the advective flows of porewater associated with burrows. Kristensen and Kostka (2005) note that "advective porewater flows may affect biogeochemical reaction zones deep in ... sediments, leading to complex redox patterns". Kristensen and Hansen (1999) demonstrated that *Nereis diversicolor* induced strong advection movements in sandy sediments but not in muddy sediments where molecular diffusion dominated solute transport. In all cases heterogeneity of sediment type is an important variable again arguing for recognition that the benthos, vertically and horizontally is a continuum.

All of these interactions are essential components of benthic -pelagic coupling which in turn is of major relevance to coastal primary production. Benthic and pelagic biodiversity reflects the benthic food web. A major source of energy for these populations is found in suspended organic particles (phytoplankton, zooplankton, organic particles) (Sokolowski et al., 2012). These organic resources support variously infaunal filter /suspension and deposit feeders that compose the benthos and variously support the nekton. Sokolowski et al. (2012) , in their analysis of benthic food webs, examined benthic organisms (greater than 1.0mm) that were found in the top 10 cm of sediments as well as epibionts living on the surface of the sediments. In this study from various marine European sites there was a positive correlation between food chain length and species richness and diversity. Over 50 years ago MacArthur (1955) suggested that stability of communities corresponded with diversity and higher numbers of trophic food web connections (stability-complexity theory). The complexity of these systems and their "energy channels" are contiguous between the nekton and benthos, including tube-dwellers, burrowers and surrounding meiofaunal and microbial communities. Bacteria are a primary food for deposit feeding organisms, both macro - and meiofauna (Gerlach, 1978) , and the nitrogenous wastes of these animals in turn provide nutrients for bacterial growth. Thus movement of sediment and fluids is important in the benthic sedimentary ecosystem. As stated by Braeckman et al. (2011) "Biological mixing influences OM (organic matter) availability (in part through) bioturbation and bio-irrigation indirectly (by) alter(ing) the distribution of small infauna through establishment of micro-habitats in the otherwise anoxic and food-depleted deep sediment layers". Essentially, bioturbation and burrowing help drive solutes, nutrients, and gases deeper into the sediments thereby "providing favourable niches to lower trophic levels" (ibid).

The burrows of infaunal organisms, as well as burrowing activity and wastes excreted and egested by these organisms, creates prime real estate for microorganisms ranging from bacteria to various phyla of deposit feeding meiofauna. Meiofauna, an "integral part of estuarine food webs" (Coull, 1999) (and very poorly known from the Passaic River), in fact, can significantly influence mineralization of organic material in muddy sediments (Nascimento et al., 2014). The links in the benthic realm extend to both positive and negative relationships between diversity and densities of macrofaunal burrows and meiofaunal populations (Moodley et al., 1998). Nematodes, an abundant if not the most abundant metazoan on Earth, are able to burrow to tens of centimeters depth in marine habitats (Heip et al., 1985). There can be interplay between macrofauna and nematodes - the number of nematode species declining with decrease in macrofaunal diversity (Ingels et al., 2014).

These various exemplars are outlined to demonstrate the deep linkage from overlying water column to deep in the sediment that composes the benthic habitat. These linkages, part of the benthic-pelagic coupling with determined and variable dependency on allochthonous input, create a bottom biotic environment that cannot be isolated to the top two centimeters of sediments. The relationship between bacteria, meiofauna and macrofauna and burrowing activity and tubes creates a living ecosystem that permeates beyond the near surface. It is well recognized that biotic system complexity, including sedimentary deeper communities linked to those nearer the surface, offer an essential "buffer against disturbance" (Godbold et al., 2011). The benthic-pelagic realm is intimately linked into deeper sediments as variously noted above. Similarly these deeper sediments are impacted by organic and inorganic contaminants either through incorporation into biotic cells and tissues, adsorption onto biological and inorganic surfaces, or through the natural hydrological cycling or water movement caused by biological activity. Heavy metal contamination, such as mercury (as methylmercury) can be found in sediments as deep as 5cm and here infaunal organisms can act as vectors to distribute this contaminant to higher trophic levels (e.g. aquatic insects that have benthic infaunal juveniles disperse into the water column and are a food resource for fish)(Tremblay et al., 1996). Specific to the Passaic River, metals, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons long ago were well documented from deeper in sediments in the lower river (Wenning et al., 1994) and certainly at sediment depths that encompass burrowing activities of extant infaunal populations.

**Methods:** Infaunal burrowing organisms reviewed in the Passaic River benthic invertebrate taxonomy and biodiversity report (Prezant, 2010) were selected for literature review to determine maximum burial depth. Because the sediments of the Passaic River vary, the data reported in table one does not take into account specific granulometry, water depth, sediment chemistry, porosity, etc. In addition, the species examined have wide geographic distributions and many have well known behaviors. Data were taken from both primary and secondary literature cited in

Table 1. Duplication of taxa in the table suggests variation in sampling protocol used by the relevant authors and/or differences in geography and habitat. The organisms evaluated in this study ranged from freshwater to estuarine and include taxa from the Nemertea, Mollusca, Annelida and Crustacea.

This review focuses on burrowing depths of infaunal invertebrate organisms that were previously retained from the Lower Passaic River Restoration Project benthic community surveys. Taxonomic verifications were prepared in a previous report by Prezant (May, 2010). Samples taken in the protocol during the Lower Passaic River Study in 2009 were washed through a 1.0mm sieve. This means that a number of smaller burrowing taxa were lost in the samples. Clearly these organisms (including nematodes) plus the microbial community play a role in the benthic infaunal environment and, as described above, can modify the organic and inorganic environment.

~



Table 1. Maximum burrowing depths for select species found in the Passaic River. Burrowing depth represents maximum depth below sediment surface in geographic location noted and from reference cited.

Taxon	Burrowing Depth [max recorded in cm]	Note	Reference
<b>Nemertea</b>			
<i>Micrura</i> sp.	15cm	Chesapeake Bay	Schaffner 1990
<b>Mollusca, Bivalvia</b>			
<i>Corbicula fluminea</i>	7cm	Lake Tahoe, NV	Wittmann et al., 2008
<i>Corbicula fluminea</i>	15cm	Rivers Barrow and Nore, Ireland	Caffrey et al. 2011
<i>Macoma balthica</i>	10cm	Chesapeake Bay	Nilsen et al. 1982
<i>Macoma balthica</i>	20cm	Global	NatureServe Explorer 2006
<i>Macoma balthica</i>	30 cm	Chesapeake Bay	Hines, A.H., A.M. Haddon and L.A. Wiechert 1990
<i>Macoma balthica</i>	To 50cm	Lynn Haven River, VA	Dauer et al. 1979
<i>Mya arenaria</i>	12cm	SW New Brunswick, Canada	Auffrey et al. 2004
<i>Mya arenaria</i>	>20cm	Lynn Haven River, VA	Dauer et al. 1979
<i>Mya arenaria</i>	5cm	Chesapeake Bay	Schaffner 1990
<i>Mya arenaria</i>	25cm	Chesapeake Bay	Blundon and Kennedy 1982
<i>Mulinia lateralis</i>	8cm	Chesapeake Bay	Nilsen et al. 1982
<i>Mulinia lateralis</i>	To 20 cm	San Pablo Bay, CA	Poulton et al. 2002
<b>Annelida, Polychaeta</b>			
<i>Hyperetone heteropoda</i>	5cm	Chesapeake Bay	Nilsen et al. 1982
<i>Hyperetone heteropoda</i>	13cm	Chesapeake Bay	Nilsen et al. 1982
<i>Marenzelleria viridis</i>	15cm	Georgia coast	Dorjes and Howard 1975
<i>Marenzelleria viridis</i>	30cm	Ems estuary, The Netherlands	Essink and Kleef 1988
<i>Marenzelleria viridis</i>	50 cm	Firth of Forth, Scotland	GB Non-natives Factsheet Editor - references therein 2011
<i>Alitta succinea</i>	10cm	Chesapeake Bay	Schaffner 1990
<i>Alitta succinea</i>	15cm	Chesapeake Bay	Hines and Comtois 1985
<i>Alitta succinea</i>	45cm	Chesapeake Bay	Nilsen et al. 1982
<i>Alitta succinea</i>	30-50 cm	Germany	Hertweck 1986 in Kristensen and Kostka 2005
<i>Pectinaria gouldii</i>	2cm	Chesapeake Bay	Schaffner 1990

<i>Pectinaria gouldii</i>	6cm	Tampa Bay, FL	Masterson and Masterson 2008
<i>Pectinaria gouldii</i>	5-7.5cm	Massachusetts	Marine Models Electronic Record <a href="http://hermes.mbl.edu/BiologicalBulletin/MMER/TWE/TweBody.html">http://hermes.mbl.edu/BiologicalBulletin/MMER/TWE/TweBody.html</a>
<i>Pectinaria gouldii</i>	30cm	Chesapeake Bay	Nilsen et al. 1982
<i>Leitoscoloplos fragilis</i>	10cm	Long Island Sound, Connecticut	Waldbusser et al. 2004
<i>Leitoscoloplos fragilis</i>	10cm	Chesapeake Bay	Nilsen et al. 1982
<i>Glycera dibranchiata</i>	20cm	Nova Scotia	DFO Canadian Science Advisory Section Report 2009
<i>Glycera dibranchiata</i>	28 cm	Chesapeake Bay	Nilsen et al. 1982
<i>Heteromastus filiformis</i>	>10cm	New Zealand	Read 2004
<i>Heteromastus filiformis</i>	>20cm	Lynn Haven River, VA	Dauer et al. 1979
<i>Heteromastus filiformis</i>	30cm	Wadden Sea	Cadée 1979
<i>Heteromastus filiformis</i>	30cm	Chesapeake Bay	Nilsen et al. 1982
<i>Capitella capitata</i>	"near surface"	New Zealand	Read 2004
<i>Glycinde solitaria</i>	2cm	Chesapeake Bay	Schaffner 1990
<i>Glycinde solitaria</i>	28cm	Chesapeake Bay	Nilsen et al. 1982
<i>Streblospio benedicti</i>	10cm	Chesapeake Bay	Nilsen et al. 1982
<i>Mediomastus (ambiseta)</i>	2cm	Chesapeake Bay	Schaffner 1990
<i>Mediomastus (ambiseta)</i>	10cm	Chesapeake Bay	Nilsen et al. 1982
<b>Annelida, Oligochaeta</b>			
<i>Limnodrilus claparedeianus</i>	13cm	Test system	Ciutat et al. 2006
<i>Limnodrilus claparedeianus</i>	33 cm	Japan	Fukuhara et al. 1987
<i>Limnodrilus claparedeianus</i>	35 cm	Messalonskee Lake, Maine	Davis 1974
<i>Limnodrilus hoffmeisteri</i>	20cm	Great Lakes	Wang 1995
<i>Tubificoides sp.</i>	5cm	Chesapeake Bay	Schaffner 1990
<b>Crustacea, Isopoda</b>			
<i>Cyathura polita</i>	5cm	Sapelo Island, GA	Frankenberg and Burbanck 1963

## Summary

Specific research to determine the exact depth of burial in infaunal organisms of the Passaic River is absent. Instead literature has been scanned to look burrowing depths of the same species in other locations. The likelihood that burrowing depths will be comparable is strong based on the variability of sedimentary types in the Passaic River and the conservative behavior of most of these organisms. The majority of infaunal benthic organisms found during the 2010 Passaic River benthic survey are known from other venues to burrow deeper than 2 cm and most burrow deeper than 5.0cm. The freshwater to low salinity non-indigenous bivalve *Corbicula fluminea* burrows as deeply as 15cm while the estuarine to saline bivalve *Macoma balthica* can reach in-sediment depths of 50cm. In the case of *C. fluminea*, the Asian clam, is able to both filter feed through siphons when closer to the surface and able to pedal feed when more deeply submerged in the sediment. *Macoma balthica* is a tellinid bivalve and as such deposit feeds through long siphons that can reach surface sediments. Both of these bivalves, as well as *Mya arenaria* and *Mulinia lateralis* are active vertical burrowers.

The polychaete annelids listed variously burrow between 2.0 and 50cm. The nereid worm *Alitta succinea*, among the more common polychaetes, is an active errant annelid that readily moves through the sediments to depths as deep as 45 cm but also moves to the surface as feeding and physiology dictate. *Glycera dibranchiata*, the predatory blood worm, actively pursues prey and is able to burrow as deeply as 28cm. *Pectinaria gouldii* is reported to be able to penetrate sediments to as deep as 30cm but is more commonly limited to total length beneath the sediment surface (reflecting the length of their carefully constructed sand tube) but this still means that their prostomium (head) can be submerged within the sediment to depths of 7.5cm. The fragile, thin and elongate polychaete *Heteromastus filiformis* and the many oligochaetes found in the Passaic River form important and dense populations. These deposit feeders can be found beneath the sediment surface as deep as 35cm for *Limnodrilus claparedeianus*.

Even delicate but predatory ribbon worm, *Micrura* sp., is able to penetrate benthic sediments to depths as much as 15cm while the isopod *Cyathura polita* builds tubes that bring it to about 5cm depth in the substratum.

Unless the benthic biota of the Passaic River are showing strongly anomalous behavior, many of these organisms readily burrow well below 2.0cm beneath the sediment surface with important implications to sedimentary structure, sediment and near surface water chemistry, local community structures resulting from bioturbation and infaunal feeding, egestive, and respiratory behaviors. The relative importance of bioengineering among infaunal organisms is reviewed by Sanders et al. (2014) with special attention to the influence biotic modification of sediments can have on the food web. Specific to the Passaic River, Germano & Associates (2005) in their report on sediment profiling discuss three infaunal successional stages that are found in the river in a patchy distribution. Stage I includes species that are opportunistic and able to tolerate "low

concentrations of dissolved oxygen and high levels of reduced sediment end products (e.g., sulfide, ammonia and methane) associated with decomposition of organic enrichment and high resultant SOD". This occurs in lower salinity portions of the river and include dominants such as (the polychaetes) *Streblospio benedicti*, *Capitella capitata*, and *Heteromastus filiformis* (note burrowing depths in Table 1). [Note: Care must be taken when determining "stages" based on feeding types as many organisms are capable of "switching" feeding mode seasonally or as induced by environmental change.] At the other end, Stage III is represented only rarely in the river and included "larger-bodied, head-down deposit feeders"(although the report notes that at Stage III sites along freshwater tidal stations "tubificid oligochaetes appeared to be the numerical dominants" (typical of many freshwater environments). The report, which reflects sediment profile imaging within the top 20 cm of sediment, confirms a "dynamic sedimentary environment" that has depositional and erosional activities on a regular basis. These cycles create a somewhat heterogeneous sediment pattern in the river benthos. While not specifically quantified, many images within this report demonstrate infaunal organisms buried or burrowed within the sediments. Extrapolating from the images cross-section widths (usually 14.6 cm) it is clear several of these organisms are submerged in the sediments to depths in excess of 2.0 cm.

The CPG consider the upper 2 cm a "primary resource" for fish and other pelagic fauna but this underplays the major contributions to the viability of the upper sediments and the contribution of organism, including bacteria and meiofauna, living deeper than the upper few centimeters. It also understates the temporal mixing of sediments, both biologically and physically induced, that must play out based on the life-styles of organisms known to inhabit the benthos of the river. Benthic-pelagic coupling is of primary importance as one reflects upon the impact that infaunal organisms can have on sediment quality and distribution, the influence of meiofauna within food webs, and the essential role sediment dwelling bacteria have in cycling nutrients. Each in their own way contributes to the cycling of water, gases, nutrients and substances of anthropogenic origins within the water column and beneath the surface sediments.

~

## Literature Cited

- Abele, D., H. Großpietsch and H.O. Pörtner. 1998. Temporal fluctuations and spatial gradients of environmental  $P_{O_2}$ , temperature,  $H_2O_2$  and  $H_2S$  in its intertidal habitat trigger enzymatic antioxidant protection in the capitellid worm *Heteromastus filiformis*. *Marine Ecology Progress Series* 163: 179-191.
- Agrawal, A. and K. Gopal. 2013. Biomass production in food chain and its role at trophic levels. Biomonitoring of Water and Waste Water. Springer Verlag, pp. 59-70.
- Aller, R.C. 1983. The importance of the diffusive permeability of animal burrow linings in determining marine sediment chemistry. *Journal of Marine Research* 41: 299-322.
- Auffrey, L.M., S.M.C. Robinson and M.A. Barbeau. 2004. Effect of green macroalgal mats on burial depth of soft-shelled clams *Mya arenaria*. *Marine Ecology Progress Series* 278: 193-203.
- Blundon, J.A. and V.S. Kennedy. 1982. Refuges for infaunal bivalves from blue crab, *Callinectes sapidus* (Rathbun), predation in Chesapeake Bay. *Journal of Experimental Marine Biology and Ecology* 61: 67-81.
- Braeckman, U., P. Provost, B. Gribsholt, D. Van Bantsbeke, J.J. Middelburg, K. Soetaert, M. Vincx and J. Vanaverbeke. 2010. Role of macrofauna functional traits and density in biogeochemical fluxes and bioturbation. *Marine Ecology Progress Series* 399: 173-186.
- Cadée, G.C. 1979. Sediment reworking by the polychaete *Heteromastus filiformis* on a tidal flat in the Dutch Wadden Sea. *Netherlands Journal of Sea Research* 13: 441-456.
- Caffrey, J.M., S. Evers, M. Millane and H. Moran. 2011. Current status of Ireland's newest invasive species – the Asian clam *Corbicula fluminea* (Müller, 1774). *Aquatic Invasions* 6: 291-299.
- Cesar, C.P. and C.L.J. Frid. 2010. Benthic disturbance affects intertidal food web dynamics: implications for investigations of ecosystem functioning. *Marine Ecology Progress Series* 466: 35-41.
- Ciutat, A., O. Weber, M. Gerino and A. Boudou. 2006. Stratigraphic effects of tubificids in freshwater sediments: a kinetic study based on x-ray images and grain-size analysis. *Acta Geologica* 30: 228-237.
- Coull, B.C. 1999. Role of meiofauna in estuarine soft-bottom habitats. *Australian Journal of Ecology* 24: 327-343.

- Dauer, D.M., W.W. Robinson, C.P. Seymour and A. T. Leggett, Jr. 1979. Effects of non-point pollution on benthic invertebrates in the Lynnhaven River system. *Bulletin of the Virginia Water Resources Research Center, Bulletin* 117, 43p.
- Davenport, E.S., D.H. Shull and A.H. Devol. 2012. Roles of sorption and tube-dwelling benthos in the cycling of phosphorus in the Bering Sea sediments. *Deep-Sea Research II*. doi: 10.1016/j.dsr2.201.02.004.
- Davis, R.B. 1974. Tubificids alter profiles of redox potential and pH in profundal lake sediment. *Limnology and Oceanography* 19: 342-346.
- de Goeij, P. and P. Luttikhuisen. 1998. Deep-burying reduces growth in intertidal bivalves: field and mesocosm experiments with *Macoma balthica*. *Journal of Experimental Marine Biology and Ecology* 228: 327-337.
- DFO. 2009. Nova Scotia bloodworm ( *Glycera dibranchiata* ) assessment: a review of methods and harvest advice. DFO Canadian Science Advisory Report 2009/037: 11 pp.
- Dorjes, J. and J.D. Howard. 1975. Estuaries of the Georgia Coast, USA: sedimentology and biology. IV. fluvial marine transition indicators in an estuarine environment, Ogeechee River - Ossabaw Sound. *Senckenbergische maritima* 7: 137-179.
- Dunne, J.A., R.J. Williams and N.D. Martinez. 2004. Network structure and robustness of marine food webs. *Marine Ecology Progress Series* 273: 291-302.
- Edelaar, P. 2000. Phenotypic plasticity of burrowing depth in the bivalve *Macoma balthica* : experimental evidence and general implications. *Geological Society, London, Special Publication* 177: 451-458.
- Esselink, P. and L. Zwarts. 1989. Seasonal trend in burrow depth and tidal variation in feeding activity of *Nereis diversicolor*. *Marine Ecology Progress Series* 56: 243-254.
- Essink, K. and H.L. Kleef. 1988. *Marenzelleria viridis* (Verril, 1873) (Polychaeta: Spionidae): a new record from the Ems Estuary (The Netherlands/Federal Republic of Germany). *Zoologische Bijdragen* 38: 1-13.
- Flynn, A.M. and D.L. Smee. 2010. Behavioral plasticity of the soft-shell clam, *Mya arenaria* (L.) in the presence of predators increases survival in the field. *Journal of Experimental Marine Biology* 383: 32-38.
- Frankenberg, D. and W.D. Burbank. 1963. A comparison of the physiology and ecology of the estuarine isopod *Cyathura polita* in Massachusetts and Georgia. *The Biological Bulletin* 125: 81-95.

Fukuhara, H., A. Ohtaka, Y. Isobe and M. Sakamoto. 1987. Seasonal changes in vertical distribution, biomass and faecal production of tubificids in the profundal region of a shallow Japanese lake. *Holarctic Ecology* 10: 8-13.

GB non -natives Factsheet Editor. 2011. *Marenzelleria viridis* , updated March 30th, 2011. [http://www.brc.ac.uk/gbnn\\_admin/index.php?q=node/231](http://www.brc.ac.uk/gbnn_admin/index.php?q=node/231)

Gerlach, S.A. 1978. Food-chain relationships in subtidal silty sand marine sediments and the role of meiofauna in stimulating bacterial productivity. *Oecologia* 33: 55-69.

Germano & Associates, Inc. 2005. Lower Passaic River Restoration Project. Sediment Profile Imaging Survey of Sediment and Benthic Habitat Characteristics of the Lower Passaic River, June 2005. G&A Project no. DS-ASI-01. Final Report. 29 pp, 24 figs, 2 Appen.

Godbold, J.A., M.T. Bulling and M. Solan. 2011. Habitat structure mediates biodiversity effects on ecosystem properties. *Proceedings of the Royal Society B* 278: 2510-2518.

Heip, C. M. Vincx and G. Vranken. 1985. The ecology of marine nematodes. *Oceanography and Marine Biology Annual Review* 23: 399-289.

Hertweck, G. 1986. Burrows of the polychaete *Nereis virens* Sars. *Senckenbergiana Maritima* 17: 319-331.

Hines, A.H. and K.L. Comtois. 1985. Vertical distribution of infauna in sediments of a subestuary of central Chesapeake Bay. *Estuaries* 8: 296-304.

Hines, A.H., A.M. Haddon and L.A. Wiechert. 1990. Guild structure and foraging impact of blue crabs and epibenthic fish in a subestuary of Chesapeake Bay. *Marine Ecology Progress Series* 67: 105-126.

Holmer, M., V.E. Forbes and T.L. Forbes. 1997. Impact of the polychaete *Capitella* sp. I on microbial activity in an organic -rich marine sediment contaminated with the polycyclic aromatic hydrocarbon fluoranthene. *Marine Biology* 128: 679-688.

Hussey, N.E., M.A. MacNeil, B.C. McMeans, J.A. Olin, S.F. > Dudley, G. C. Clif, S.P. Wintner, S.T. Fennessy and A.T. Fisk. 2013. Rescaling the trophic structure of marine food webs. *Ecology Letters* doi: 10.1111/ele.12226.

Ingels, J., S.L. Dashfield, P.J. Somerfield, S. Widdicombe and M.C. Austen. 2014. Interactions between multiple large macrofauna species and nematode communities - Mechanisms for indirect impacts of trawling disturbance. *Journal of Experimental Marine Biology and Ecology* 456: 41-49.

Jones, C.G., J.E. Byers, J.A. Crooks, J.G. Lambrinos and T.S. Talley. 2010. A framework for understanding physical ecosystem engineering by organisms. *Oikos* 119: 1862-1957.

Jonsson, T. 2014. Trophic links and the relationship between predator and prey body sizes in food webs. *Community Ecology* 15: 54-64.

Kristensen, E., and K. Hansen. 1999. Transport of carbon dioxide and ammonium in bioturbated (*Nereis diversicolor*) coastal, marine sediments. *Biogeochemistry* 45: 147-168.

Kristensen, E. and J.E. Koska. 2005. Macrofaunal burrows and irrigation in marine sediment: microbiological and biogeochemical interactions. *Coastal and Estuarine Studies* 60: 125-157.

Krumins, J.A., D. Van Ovelen, T.M. Bezemer, G. B. De Deyn, W.H. Gera Hol, E. Van Donk, W. De Boer, P.C. De Ruiter, J.J. Middelburg, F. Monroy, K. Soetaert, El Thébault, J. Van De Koppel, J.A. Van Veen, M. Viketoft and W.H. Van Der Putten. 2013. Soil and freshwater and marine sediment food webs: their structure and function. *BioScience* 63: 35-42.

Laverock, B., J.A. Gilbert, K. Tait, A. M. Osborn and S. Widdicombe. 2011. Bioturbation: impact on the marine nitrogen cycle. *Biochemical Society Transactions* 39: 315-320.

MacArthur, R.H. 1955. Fluctuation of animal populations and a measure of community stability. *Ecology* 36: 533-536.

Marine Models Electronic Record

<http://hermes.mbl.edu/BiologicalBulletin/MMER/TWE/TweBody.html>

Masterson, W.S. and J. Masterson. 2008. Smithsonian Marine Station at Fort Pierce report: *Pectinaria gouldii*. [http://www.sms.si.edu/irlspec/Pectinaria\\_gouldii.htm](http://www.sms.si.edu/irlspec/Pectinaria_gouldii.htm)

Moodley, L., C.H.R. Heip and J.J. Middelburg. 1998. Benthic activity in sediments of the northwestern Adriatic Sea: sediment oxygen consumption, macro - and meiofauna dynamics. *Journal of Sea Research* 40: 263-280.

Nascimento, F.J.A., J. Näslund and R. Elmgren. 2014. Meiofauna enhances organic matter mineralization in soft sediment ecosystems. *Limnology and Oceanography* 57: 338-346.

NatureServe Explorer 2006. *Macoma balthica* - (Linnaeus, 1758). July 2013. <http://explorer.natureserve.org/servlet/NatureServe?searchName=Macoma+balthica>

Nilsen, K.J., R.J. Diaz, L.C. Schaffner, D.F. Boesch, R. Bertelsen and M. Kravitz. 1982. The biogenic structure of the Lower Chesapeake Bay sediments. EPA Chesapeake Bay Program Final Report, Grant R805982-01-0. 257p.



Poulton V.K., J.R. Lovvorn and J.Y. Takekawa. 2002. Clam density and scaup feeding behavior in San Pablo Bay, California. *The Condor* 104: 518-527.

Prezant, R.S. 2010. Lower Passaic River Restoration Project – CPG Oversight. Benthic invertebrate confirmations. KC-ACE2008-34. Report to Louis Berger Group, Inc. and Army Corp of Engineers. 15 pp.

Quintana, C.O., T. Hansen, M. Delefosse, G. Banta and E. Kristensen. 2011. Burrow ventilation and associated porewater irrigation by the polychaete *Marenzelleria viridis*. *Journal of Experimental Marine Biology and Ecology* 397: 179-187.

Read, G.B. 2004. Guide to New Zealand shell polychaetes. National Institute of Water and Atmospheric Research, New Zealand (NIWA). <http://biocollections.org/pub/worms/nz/Polychaeta/ShellsPoly/NZShellsPolychaeta.htm>

Reed, H.E. and J. B.H. Martiny. 2013. Microbial composition affects the functioning of estuarine sediments. *The ISME Journal* 7: 868-879.

Reinharz, E. and A. O'Connell. 1983. Animal -sediment relationships of the Upper and Central Chesapeake Bay. *U.S. EPA Chesapeake Bay Program*, Report no. EPA- 600/3-83-033.

Riisgård, H.U. and P. Kamermans. 2001. Switching between deposit and suspension feeding in coastal zoobenthos. *Ecological Studies* 151: 73-101.

Rönn, C., E. Bonsdorf and W. Nelson. 1988. Predation as a mechanism of interference within infauna in shallow brackish water soft bottoms; experiments with an infauna predator, *Nereis diversicolor* O.F. Müller. *Journal of Experimental Marine Biology and Ecology* 116: 143-157.

Sanders, D., C.G. Jones, E. Thébault, T.J. Bouma, T. van der Heide, J. van Belzen and S. Barot. 2014. Integrating ecosystem engineering and food webs. *Oikos* 123: 513-524.

Schaffner, L.C. 1990. Small -scale organism distribution and patterns of species diversity: evidence for positive interactions in an estuarine benthic community. *Marine Ecology Progress Series* 61: 107-117.

Snelgrove, P.V.R. and C.A. Butman. 1994. Animal -sediment relationships revisited: cause versus effect. *Oceanography and Marine Biology Annual Review* 32: 111-177 In: *Oceanography and Marine Biology: An Annual Review*. Aberdeen University Press/Allen & Unwin: Aberdeen.

Sokolowski, A., M. Wolowicz, H. Asmus, R. Asmus, A. Carlier, Z. Gasluaite, A. Grémare, H. Hummel, J. Lesutiené, A. Razinkovas, P.E. Renaud, P. Richard and M. Kędra. 2012. Is benthic food web structure related to diversity of marine macrobenthic communities? *Estuarine, Coastal and Shelf Science* 108: 76-86.

Takahashi, D., A. Brännström, R. Mazzucco, A. Tamauchi and U. Dieckmann. 2013. Abrupt community transitions and cyclic evolutionary dynamics in complex food webs. *Journal of Theoretical Biology* 337: 181-189.

Thomson, E. 2011. Soft shell clam, *Mya arenaria*, burrow depth response to European green crab, *Carcinus maenas*, predators in different sediment types. *Kent Island Fellowship report*. <http://www.bowdoin.edu/student-fellowships/pdf/summer-2010/e-thomson.pdf>.

Thomson, E. and D.P. Gannon. 2013. Influence of sediment type on antipredator response of the softshell clam, *Mya arenaria*. *Northeastern Naturalist* 20: 498-510.

Tremblay, A., M. Lucotte and I. Rheault. 1996. Methylmercury in a benthic food web of two hydroelectric reservoirs and a natural lake of northern Quebec (Canada). *Water, Air, and Soil Pollution* 91: 255-269.

Turner, E.J. and D.C. Miller. 1991. Behavior of a passive suspension-feeder (*Spiochaetopterus oculatus* (Webster)) under oscillatory flow. *Journal of Experimental Marine Biology and Ecology* 149: 123-137.

Vaughn, C.C. and C. Hakenkamp. 2001. The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology* 46: 1431-1446.

Waldbusser, G.G., R.L. Marinelli, R.B. Whitlatch and P.T. Visscher. 2004. The effects of infaunal biodiversity on biogeochemistry of coastal marine sediments. *Limnology and Oceanography* 49: 1482-1492.

Wang, Xiaosong. 1995. Biogenic mass transport in Great Lakes sediments. Electronic Thesis or Dissertation. Case Western Reserve University. *OhioLINK Electronic Theses and Dissertations Center*. 20 Apr 2014.

Wenning, R.J., N.L. Bonnevie and S.L. Huntley. 1994. Accumulation of metals, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons in sediments from the Lower Passaic River, New Jersey. *Archives of Environmental Contamination and Toxicology* 27: 64-81.

Werner, S. and K. -O. Rothhaupt. 2007. Effects of the invasive bivalve *Corbicula fluminea* on settling juveniles and other benthic taxa. *Journal of the North American Benthological Society* 26: 673-680.

Whitlatch, R.B. 1981. Animal sediment relationships in intertidal marine benthic habitats: some determinants of deposit-feeding species diversity. *Journal of Experimental Marine Biology and Ecology* 53: 31-45.

Williams, R.J. and N.D. Martinez. 2004. Limits to trophic levels and omnivory in complex food webs: theory and data. *The American Naturalist* 163: 458-468.

Wittmann, M.E., S. Chandra, J.E. Reuter, S.G. Schladow, B.C. Allen and K.J. Webb. 2012. Expanded Asian Clam Control Project. Tahoe Environmental Research Center, University of California at Davis and Aquatic Ecosystems Lab, University of Nevada at Reno. Final report submitted to the Nevada Division of State Lands. 36 p.

Zhang, L., Q. Shen, H. Hu, S. Shao and C. Fan. 2011. Impacts of *Corbicula fluminea* on oxygen uptake and nutrient fluxes across the sediment-water interface. *Water, Air and Soil Pollution* 220: 399-411.

Zwarts, L. and J. Wanink. 1989. Siphon size and burying depth in deposit- and suspension-feeding benthic bivalves. *Marine Biology* 100: 227-240.